# CERTIFICATE OF GRANT OF PATENT

In accordance with Section 24(2) of the Patents Act, 1977, it is hereby certified that a patent having the specification No 2301852 has been granted to Smith International Inc, in respect of an invention disclosed in an application for that patent having a date of filing of 31 May 1996 being an invention for "Drill bit and cutting structure having enhanced placement and sizing of cutters for improved bit stabilization"

Dated this Thirtieth day of June 1999

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**Comptroller-General of Patents, Designs and Trade Marks.**
UNITED KINGDOM PATENT OFFICE

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(54) Title of Invention

# Drill bit and cutting structure having enhanced placement and sizing of cutters for improved bit stabilization

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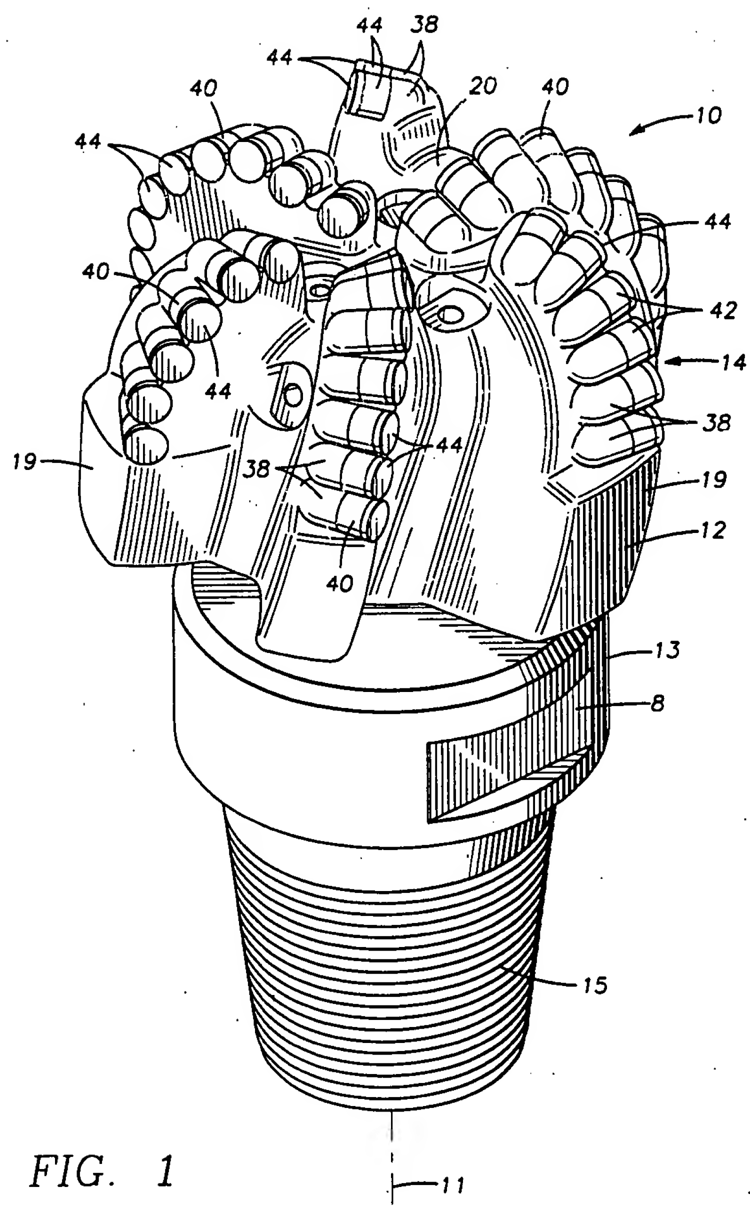


FIG. 1

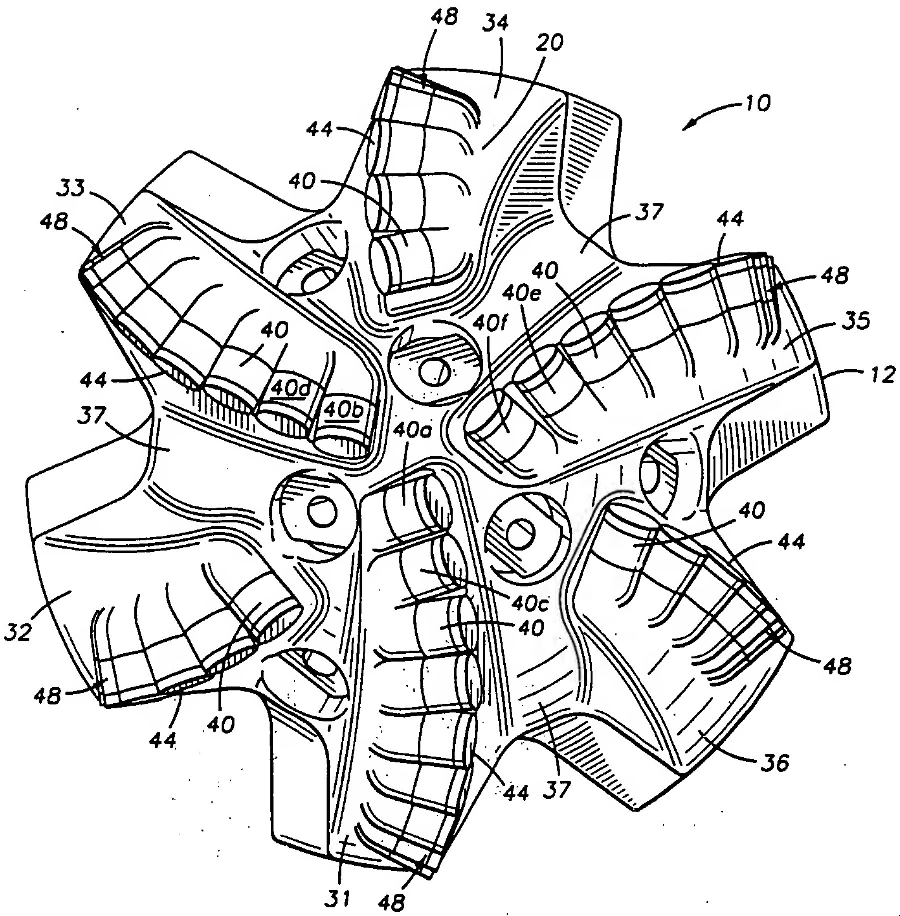

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FIG. 2

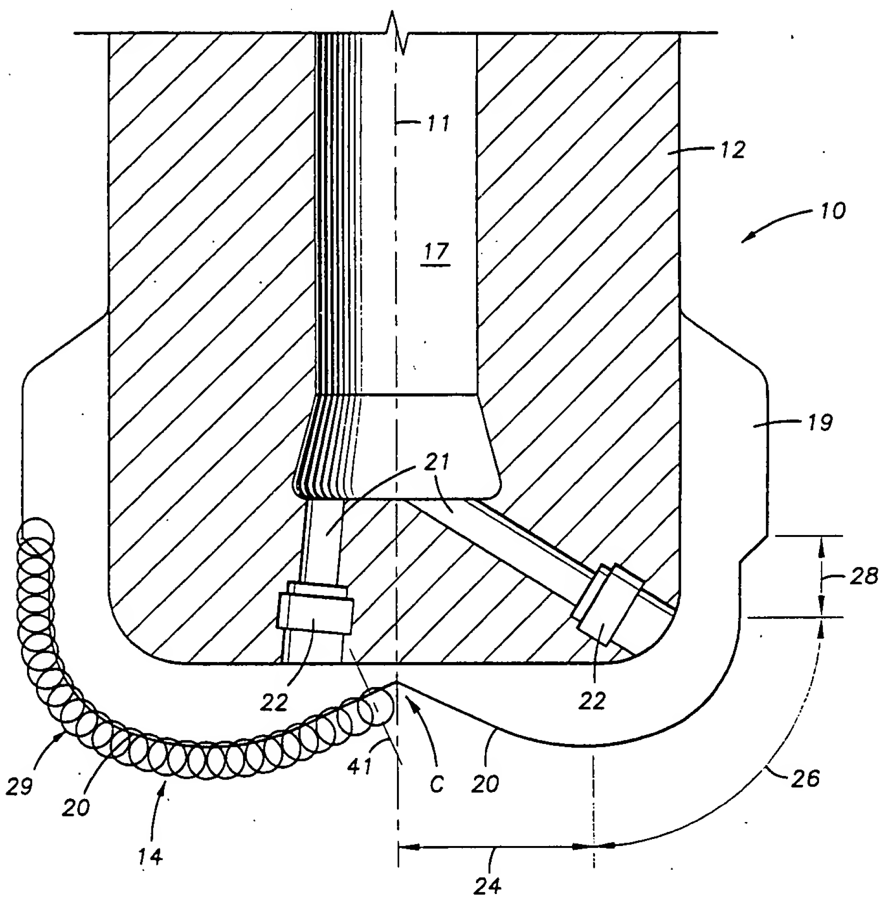
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FIG. 3

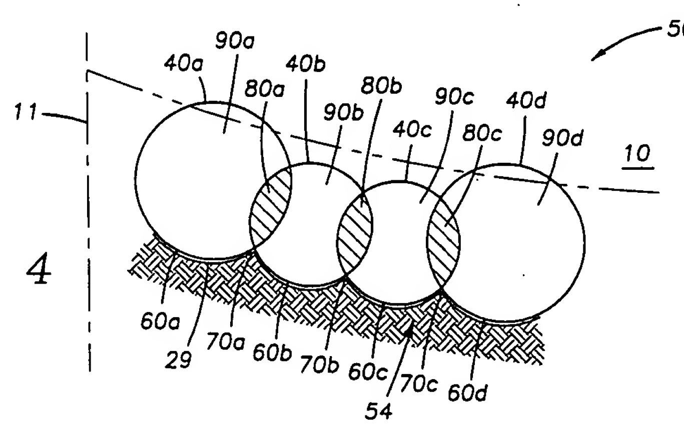
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FIG. 4

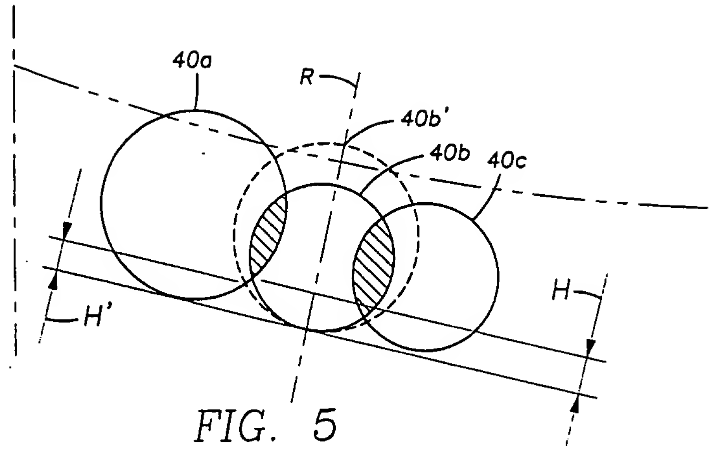


FIG. 5

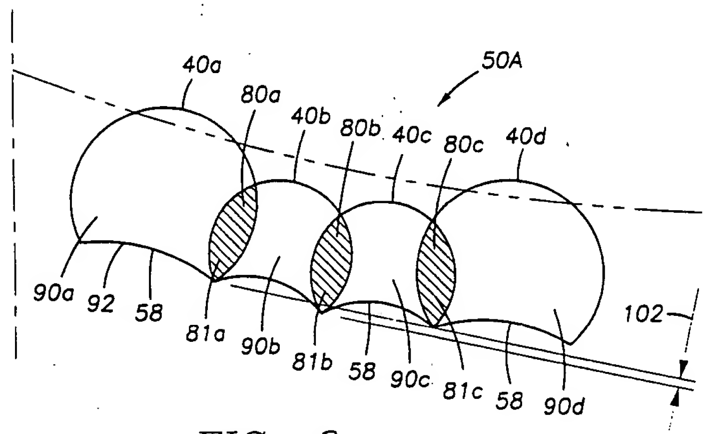


FIG. 6

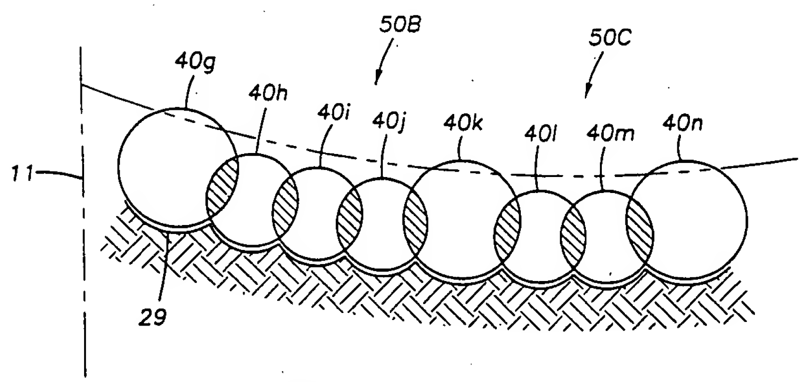


FIG. 7

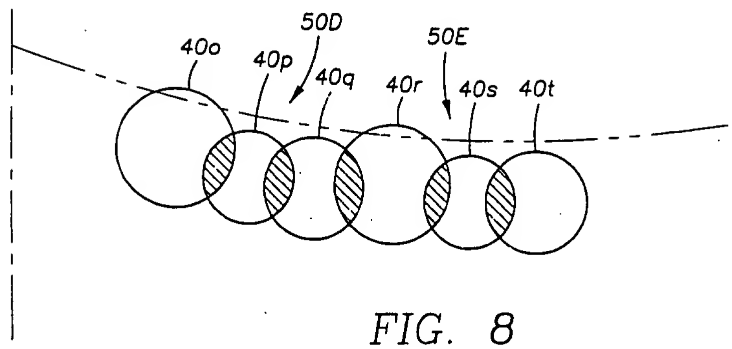


FIG. 8

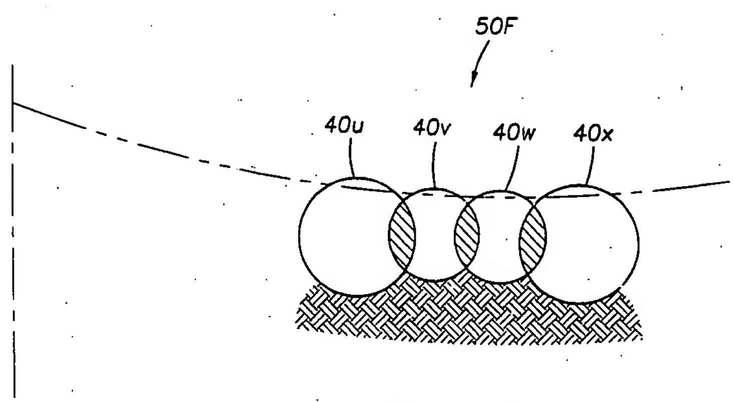


FIG. 9

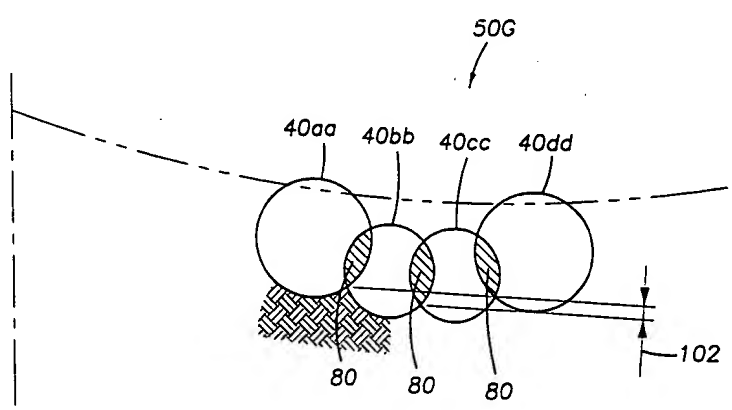


FIG. 10

2301852



# DRILL BIT AND CUTTING STRUCTURE HAVING ENHANCED PLACEMENT AND SIZING OF CUTTERS FOR IMPROVED BIT STABILIZATION

## DESCRIPTION

This invention relates generally to drill bits. The invention has application to fixed cutter drill bits of the type used in cutting rock formation such as used in drilling an oil well or the like. More particularly, the invention relates to bits utilizing polycrystalline diamond cutting elements that are mounted on the face of the drill bit, such bits typically being referred to as "PDC" bits.

In drilling a borehole in the earth, such as for the recovery of hydrocarbons or for other applications, it is conventional practice to connect a drill bit on the lower end of an assembly of drill pipe sections which are connected end-to-end so as to form a "drill string". The drill string is rotated by apparatus that is positioned on a drilling platform located at the surface of the borehole. Such apparatus turns the bit and advances it downwards, causing the bit to cut through the formation material by either abrasion, fracturing, or shearing action, or through a combination of all cutting methods. While the bit is rotated, drilling fluid is pumped through the drill string and directed out of the drill bit through flow channels that are formed in the bit. The drilling fluid is provided to cool the bit and to flush cuttings away from the cutting structure of the bit and upwardly into the annulus formed between the drill string and the borehole.

Many different types of drill bits and cutting structures for bits have been developed and found useful in drilling such boreholes. Such bits include fixed cutter bits and roller cone bits. The types of cutting structures include milled tooth bits, tungsten carbide insert ("TCI") bits, PDC bits, and natural diamond bits. The selection of the appropriate bit and cutting structure for a given

application depends upon many factors. One of the most important of these factors is the type of formation that is to be drilled and, more particularly, the hardness of the formation that will be encountered. Another important consideration is the range of hardnesses that will be encountered when drilling through layers of differing formation hardness.

Depending upon formation hardness, certain combinations of the above-described bit types and cutting structures will work more efficiently and effectively against the formation than others. For example, a milled tooth bit generally drills relatively quickly and effectively in soft formations, such as those typically encountered at shallow depths. By contrast, milled tooth bits are relatively ineffective in hard rock formations such as may be encountered at greater depths. For drilling through such hard formations, roller cone bits having TCI cutting structures have proven to be effective. For certain hard formations, fixed cutter bits having a natural diamond cutting structure provide the best combination of penetration rate and durability. In formations of soft and medium hardness, fixed cutter bits having a PDC cutting structure are employed with good results.

The cost of drilling a borehole is proportional to the length of time it takes to drill the borehole to the desired depth and location. The drilling time, in turn, is greatly affected by the number of times the drill bit must be changed before reaching the targeted formation. This is the case because each time the bit is changed the entire drill string, which may be miles long, must be retrieved from the borehole section by section. After the drill string is retrieved and the new bit installed, the bit must be lowered to the bottom of the borehole on the drill string which again must be constructed section by section. As is thus obvious, this process, known as a "trip" of the drill string, requires considerable time, effort and

expense. Accordingly, it is always desirable to employ drill bits which will drill faster and longer and which are usable over a wider range of differing formation hardnesses.

The length of time that a drill bit may be employed before it must be changed depends upon its durability or ability to maintain a high or acceptable rate of penetration ("ROP"). Additionally, a desirable characteristic of the bit is that it be "stable" and resist vibration, the most severe type or mode of which is "whirl", which is a term used to describe the phenomenon where a drill bit rotates at the bottom of the borehole about a rotational axis that is offset from the geometric centre of the drill bit. Such whirling subjects the cutting elements on the bit to increased loading, which causes the premature wearing or destruction of the cutting elements and decreased penetration rates.

In recent years, the PDC bit has become an industry standard for cutting formations of soft and medium hardnesses. The cutting elements used in such bits are formed of extremely hard materials and include a layer of polycrystalline diamond material. In the typical PDC bit, each cutter element or assembly comprises an elongate and generally cylindrical support member which is received and secured in a pocket formed in the surface of the bit body. A disk or tablet-shaped, preformed cutting element having a thin, hard cutting layer of polycrystalline diamond is bonded to the exposed end of the support member, which is typically formed of tungsten carbide.

As PDC bits were being developed for use in harder formations, their cutting structures were, in many instances, designed so as to be "heavy set", which means that the bit was provided with a large number of cutter elements distributed about the face of the bit such that each of the elements would remove a comparatively small amount of material from the formation during each

revolution and would be subjected to a loading that was less than the loading that would be experienced by the cutter elements if fewer cutter elements were provided. This arrangement is to be contrasted with a "light set" bit which had proven successful in softer formations and which has comparatively fewer but larger sized cutter elements, each of which would remove a greater volume of formation material than the elements used in a "heavy set" bit.

Because of the difference in design and construction of the heavy set and light set PDC bits, inefficiencies resulted when using one of these bit designs to drill through formations of differing hardness. For example, if a heavy set bit was used for the reason that a lower formation layer had a relatively high degree of hardness compared to a softer upper layer, the heavy set bit tended to clog in the softer formations, resulting in a reduced ROP in that section of the borehole. Alternatively, if a light set bit was used, the ROP in the hard formation was relatively slow in comparison to the rate that could be achieved using a heavy set bit. Thus, where PDC bits were to be used, it was frequently necessary to accept lower ROPs while drilling through formations of one degree of hardness or another, or to trip the drill string and change the drill bits when drilling through formations of differing hardness. Either of these alternatives could be extremely costly.

A common arrangement of the PDC cutting elements was at one time to place them in a spiral configuration. More specifically, the cutter elements were placed at selected radial positions with respect to the central axis of the bit, with each element being placed at a more remote radial position than the preceding element. So positioned, the path of all but the centre-most elements partly overlapped the path of movement of a preceding cutter element as the bit was rotated. Thus, each element would remove a lesser volume of material than would be the case if it were

radially positioned so that no overlapping occurred, or occurred to a lesser extent, because the leading cutter element would already have removed some formation material from the path travelled by the following cutter element. Using this arrangement, each cutter tended to remove a comparatively small amount of material from the formation during each revolution, and was subjected to substantially the same loading as the other cutter elements on the bit face.

Although the spiral arrangement was once widely employed, this arrangement of cutter elements was found to wear in a manner to cause the bit to assume a cutting profile presenting a relatively flat and single continuous cutting edge from one element to the next. Not only did this decrease the ROP that the bit could provide, it also increased the likelihood of bit vibration. Both of these conditions are undesirable. A low ROP increases drilling time and cost and may necessitate a costly trip of the drill string in order to replace the dull bit with a new bit. Excessive bit vibration will itself dull or damage the bit to the extent that a premature trip of the drill string becomes necessary.

Thus, in addition to providing a bit capable of drilling effectively at desirable ROPs through a variety of formation hardnesses, preventing bit vibration and maintaining stability of PDC bits has long been a desirable goal, but one which has not always been achieved. Bit vibration typically may occur in any type of formation, but is most detrimental in the harder formations. As described above, the cutter elements in many prior art PDC bits were positioned in a spiral relationship which, as drilling progressed, wore in a manner which caused the ROP to decrease and which also increased the likelihood of bit vibration.

There have been a number of designs proposed for PDC cutting structures that are meant to provide a PDC bit

capable of drilling through a variety of formation hardnesses at effective ROPs and with acceptable bit life or durability. For example, US-A-5033560 describes a PDC bit having mixed sizes of PDC cutter elements with larger cutter elements positioned near the central axis of the bit and cutters of decreasing diameter at positions more distant from the central axis. This arrangement was intended to provide improved ROP while maintaining bit durability, but because the bit tends to wear in a pattern producing a relatively smooth cutting profile, the bit tends to be unstable, particularly in hard rock formations. Similarly, US-A-5222566 describes a drill bit which employs PDC cutter elements of differing sizes, with the larger size elements employed in a first group of cutters disposed on a first blade and smaller size cutters employed in a second group on a second blade. This bit also presents a relatively smooth cutting profile to the formation which limits the bit's ability to resist vibration. This design also suffers from the fact that the bit blades do not share the cutting load equally. Instead, the blade on which the larger sized cutters are mounted is loaded to a greater degree than the blade with the smaller cutter elements. This could lead to blade failure. US Re 33757 describes a bit with an arrangement of blunt and scribe shaped cutters wherein the scribe cutters are located directly before and between blunt cutting elements. The scribe cutters are intended to prefracture formation material and leave a series of kerfs. Following the scribe cutters are a series of blunt cutters intended to dislodge formation from between the kerfs. While this design was intended to enhance drilling performance in formations classified as medium-soft to medium, this bit includes no features directed toward stabilizing the bit once wear has commenced. Further, the bit's cutting structure has been found to limit the bit's application to relatively brittle formations.

Separately, other attempts have been made to design bits that will minimize or prevent bit vibration. For example, US Re 34435 describes a bit having a set of cutters which are disposed at an equal radius from the centre of the bit and which extend further from the bit face than the other cutters on the bit. According to US Re 34435, the set of cutters extending furthest from the bit face are provided so as to cut a circular groove within the formation. In this design, the extending cutters are meant to ride in the groove in order to stabilize the bit. Similarly, US-A-5265685 discloses a PDC bit that is designed to cut a series of grooves in the formation such that the resulting ridges that are formed between the concentric grooves will tend to stabilize the bit. US-A-5238075 describes a PDC bit having a cutter element arrangement intended to provide stabilization which employs cutter elements of different sizes. However, the design taught in US-A-5238075 discloses mounting the smaller cutter elements such that, in rotated profile, their cutting profiles fall entirely within the cutting profiles of larger elements. This arrangement requires that a relatively large number of large cutter elements be positioned on the bit face. This limits the number of cutter elements that can be mounted on the bit face and, in turn, decreases the total surface area of diamond material available for cutting the formation material.

Additionally, many of these designs aimed at minimizing bit vibration required that drilling be conducted with an increased weight-on-bit (WOB) as compared with bits of earlier designs. Increasing the WOB is accomplished by adding additional heavy drill collars to the drill string in order to provide acceptable penetration rates. However, drilling with an increased or heavy WOB has serious consequences and is avoided whenever possible. The additional weight increases the stress and strain on all drill string components, causes stabilizers to wear

more quickly and to work less efficiently, and increases the hydraulic pressure drop in the drill string, requiring the use of higher capacity (and typically higher cost) pumps for circulating the drilling fluid.

Thus, despite attempts and certain advances made in the art, there remains a need for a PDC bit having an improved cutter arrangement which will permit the bit to drill effectively at economical ROPs, and that will provide an increased measure of stability, both initially and as wear occurs. More specifically, there is a need for a PDC bit which can drill in soft, medium, medium hard and even in some hard formations while maintaining an aggressive cutter profile so as to maintain good ROPs for acceptable lengths of time and thereby lower the drilling costs presently experienced in the industry. Ideally, such a bit would provide an increased measure of stability so as to resist bit vibration without having to employ substantial additional WOB.

According to a first aspect of the present invention, there is provided a drill bit for drilling through formation material when the bit is rotated about its axis, the drill bit comprising: a bit body including a bit face having a plurality of radially disposed blades angularly spaced from one another; and, cutter elements disposed in rows on the blades and having cutting faces oriented so as to cut kerfs in the formation material when the bit is rotated about its axis, the cutter elements including a first plurality with cutting faces having a radius of curvature, a second plurality with cutting faces having a radius of curvature that is less than the radius of curvature of the cutting faces of the first plurality, and a third plurality with cutting faces having a radius of curvature that is greater than the radius of curvature of the cutting faces of the second plurality, at least one of the blades having a row of cutter elements that includes cutter elements from at least two of the first, second and

third pluralities; wherein the cutter elements are arranged in sets of cutter elements on the bit face, each of the cutter elements of the sets having a cutting profile that, in rotated profile, partially overlaps with the cutting profile of at least one other cutter element of the same set; wherein a first set includes a first cutter element of the first plurality mounted on a first blade at a first radial position relative to the bit axis, a second cutter element of the second plurality mounted on a second blade at a second radial position relative to the bit axis such that the cutting profile of the second cutter element partially overlaps in rotated profile with the cutting profile of the first cutter element, and a third cutter element of the third plurality mounted at a third radial position relative to the bit axis; and, wherein the second radial position is between the first and the third radial positions.

The radius of curvature of the cutter faces of the third plurality may be substantially equal to the radius of curvature of the cutter faces of the first plurality.

The radius of curvature of the cutter faces of the third plurality may be greater than the radius of curvature of the cutter faces of the first plurality.

The radius of curvature of the cutter faces of the third plurality may be less than the radius of curvature of the cutter faces of the first plurality.

Said first blade may include a row of cutter elements that includes cutter elements from all of the first, second and third pluralities. Each of the blades of the bit face may include a row of cutter elements that includes cutter elements from all of the first, second and third pluralities.

The first set may further comprise a fourth cutter element having a cutting face with a radius of curvature that is substantially equal to the radius of curvature of the second cutter element, and wherein the fourth cutter

element is mounted at a radial position that is between the second and third cutter elements when viewed in rotated profile, and wherein the radius of curvature of the cutter faces of the third plurality is greater than the radius of curvature of the cutter faces of the first plurality.

According to a second aspect of the present invention, there is provided a cutting structure for a drill bit, the cutting structure comprising: a bit face having a central axis; cutter elements having cutting profiles and generally circular cutting faces mounted on the bit face in radially-disposed rows on blades, the cutter elements including a first plurality having cutting faces of a first diameter, a second plurality having cutting faces of a second diameter that is smaller than the first diameter, and a third plurality having cutting faces of a third diameter that is larger than the second diameter; wherein a first and a second of the rows of cutter elements each includes cutter elements from the first and the second pluralities, the cutter elements in each of the first and second rows being radially spaced from one another; wherein the cutter elements are mounted on the bit face in sets of cutter elements, a first set including a first cutter element of the first plurality and a second cutter element of the second plurality mounted in separate ones of the rows of cutter elements and at different radial positions relative to the axis such that, in rotated profile, the cutting profiles of the first and the second cutter elements partially overlap and such that the first cutter element is mounted closer to the axis than the second cutter element, the first set further including a third cutter element of the third plurality mounted on the bit face at a third radial position that is further from the axis than the first and the second radial positions; and, wherein at least two of the first, second and third cutter elements reside on one of said blades.

The third diameter may be larger than the first diameter.

The third diameter may be smaller than the first diameter.

The third diameter may be substantially the same size as the first diameter.

Accordingly, in the preferred embodiment, there is provided herein a drill bit and cutting structure particularly suited for drilling through a variety of formation hardnesses at improved penetration rates. Using normal WOB, the bit and cutting structure provide enhanced stability, both when the bit is initially placed in service and after substantial wear has occurred. The bit combines the shearing efficiency of relatively large cutter elements with the prefracturing that may be provided by smaller cutters in some formations.

In the preferred embodiment, the bit generally includes a cutting structure having spaced apart sets of cutter elements mounted on the bit face. The cutter elements in each set are likewise spaced apart along the bit face. A cutter set includes a plurality of cutter elements, at least two of which have cutting faces with different radii of curvature. In embodiments having generally circular cutting faces, the cutting faces of the cutter elements within the set will have different diameters. The large and small cutter

elements in a set are mounted with overlapping profiles when viewed in a rotated profile. Larger diameter cutter elements cut a wider kerf having a larger arc while smaller diameter cutters create narrower kerfs with a smaller arc. The positioning of a large and small cutter elements with overlapping profiles creates stabilizing ridges that are larger than those that would be formed if identically-sized cutters were employed. The overlapping cutting profiles of elements in a set create regions of multiple diamond density that are better able to resist wear than regions that do not overlap the cutting profiles of radially-adjacent cutter elements. With cutter elements having generally circular cutting faces, these regions of multiple diamond density form relatively sharp, elongate cutting profiles. After the bit wears, these regions create a secondary pattern of kerfs and ridges in the formation material so as to provide enhanced bit stability even after substantial wear has occurred to the bit's cutting structure.

Additional advantages accrue through the use of different sized cutter elements. For example, the smaller diameter cutter elements direct more force downward into the formation material and may thereby prefracture the formation material. The consequent weakening of the formation allows the larger cutters to cut through the formation more efficiently, and generally allows the bit to drill through harder formation materials than would otherwise be possible. In softer formations, the large diameter cutters more efficiently remove soft formation material than the smaller cutters. Thus, the bit is especially effective when used to drill through a series of successive layers of differing formation hardness.

The cutter elements in a set may have two, three or more different diameters depending upon the formation material to be drilled. One or a plurality of relatively small cutter elements may be disposed between the larger

cutter elements, as viewed in rotated profile. Further, the size of the stabilizing kerfs and ridges formed in the formation material can be altered by varying the exposure height of the small or large cutter elements.

Thus, the present invention comprises a combination of features and advantages which enable it to substantially advance the drill bit art by providing a cutting structure and drill bit for effectively and efficiently drilling through a variety of formation hardnesses at economic rates of penetration. The bit provides an enhanced measure of bit stability, both before and after substantial wear has occurred to the cutting structure of the bit. Stability of the bit does not depend upon providing additional or excessive WOB. Employing the relatively small cutter elements allows the bit to be made relatively heavy set. Also, in certain formations, the smaller cutter elements of the bit prefracture the formation material, allowing the larger cutter elements to efficiently remove the material.

These and various other characteristics and advantages of the present invention will be readily apparent to those skilled in the art upon reading the following detailed description of the preferred embodiments of the invention, and by referring to the accompanying drawings.

For a detailed description of the preferred embodiment of the invention, reference will now be made to the accompanying drawings, wherein:

Figure 1 is a perspective view of a drill bit and cutting structure made in accordance with the present invention;

Figure 2 is a plan view of the cutting end of the drill bit shown in Figure 1;

Figure 3 is an elevational view, partly in cross-section, of the drill bit shown in Figure 1 with the cutter elements shown in rotated profile collectively on one side of the central axis of the drill bit;

26 and 28. The central portion of the bit face 20 is identified by the reference numeral 24 and may be concave as shown. Adjacent to central portion 24 is the shoulder or the upturned curved portion 26. Next to shoulder portion 26 is gage portion 28, which defines the diameter or gage of the borehole drilled by bit 10. As will be understood by those skilled in the art, regions 24, 26 and 28 are approximate and are identified only for the purposes of better describing the distribution of cutter elements 40 over the cutting structure 14 and bit face 20. Figure 3 depicts the cutter elements 40 of the bit 10 in rotated profile collectively on one side of central bit axis 11. As will be apparent from the description that follows, the invention contemplates the use of cutter elements 40 having different sizes or radii of curvature. The differences in the curvature and size of the cutting faces 44 of the various cutter elements 40 is not visible in Figures 1-3, but is described in more detail below with reference to Figures 4-10.

As best shown in Figures 1 and 2, moulded into each blade of bit 10 are a series of cutter pockets 38 for mounting cutter elements 40. Cutter elements 40 are constructed by conventional methods and each typically includes a base or support member 42 having one end secured within cutter pocket 38 by brazing or similar means. The support 42 is comprised of a sintered tungsten carbide material having a hardness greater than that of the body matrix material of bit body 12. Attached to the opposite end of the support member 42 is a layer of extremely hard material, preferably a synthetic polycrystalline diamond material which forms the cutting face 44 of element 40. Such cutter elements 40, generally known as polycrystalline diamond composite compacts, or PDCs, are commercially available from a number of suppliers including, for example, Smith Sii Megadiamond, Inc., General Electric Company or DeBeers Industrial Diamond Division. Although

cutters 40 have thus far been shown and described as generally cylindrical elements, the bit 10 and cutting structure 14 of the present invention is not limited to any particular type of cutter element, and stud-type cutters which have cutting faces 44 mounted on posts or studs that are fixed normal to the bit face may also be employed.

As shown in Figures 1 and 2, the cutter elements 40 are arranged in separate rows 48 along the blades 31-36 and are positioned along the bit face 20 in the regions previously described as the central portion 24, shoulder 26 and gage portion 28. Cutter elements 40 of rows 48 are mounted on blades 31-36 in predetermined radially-spaced positions relative to the central axis 11 of the bit 10. The cutting faces 44 of the cutter elements 40 are oriented in the direction of rotation of the drill bit 10 so that the cutting face 44 of each cutter element 40 engages the earth formation as the bit 10 is rotated and forced downwardly through the formation. Cutter elements 40 in rows 48 are radially spaced in rows 48 such that the groove or kerf cut in the formation material by the cutting face 44 of a cutter element 40 will overlap to a degree with kerfs formed by cutter elements of other rows 48. In this manner, as bit 10 is rotated, cutter elements 40 in the row 48 of blade 31, for example, will cut separate kerfs in the formation material, leaving ridges of formation material between those kerfs. As the bit 10 continues to rotate, various cutter elements 40 that are mounted on blades 32-36 will cut the formation material that is left between the kerfs formed by the cutter elements 40 of blade 31. With this radial overlap of cutter 40 profiles, the cutting profile of cutting structure 14 may be generally represented by the scalloped curve 29 shown in Figure 3 which is formed by the outermost edges of cutting faces 44 of cutters 40. It is to be understood, however, that a principle of the present invention is to provide a bit face 20 with cutting structure 14 that will provide enhanced bit

stability, both initially and after wear has occurred. This is accomplished by properly sizing and positioning cutter elements 40 so that they will create stability-enhancing ridges of formation material when the bit is rotated. Thus, although bit cutting profile 29 appears in Figure 3 to be relatively smooth or only slightly scalloped, the stabilizing ridges and the relative size and placement of cutter elements 40 that create the ridges is better depicted in Figures 4-10 and described in the accompanying text.

In addition to being mounted in rows 48, cutter elements 40 are also arranged in sets 50, each set 50 including cutter elements 40 from various rows 48. Each set 50 includes at least three radially-spaced cutter elements, at least two of which have cutting faces 44 with differing radii of curvature. When employing cutters having substantially circular cutting faces, this arrangement is achieved by choosing cutters 40 having cutting faces of differing diameters. The precise radial positioning and differences in diameter of the cutter elements 40 in the sets 50 are not visible in Figure 3, but are described in more detail below with reference to Figures 4-10.

Cutter sets 50 are best understood with reference first to Figure 4 which schematically shows, in rotated profile, the relative radial positions and sizes of the most centrally located cutter elements 40a-40d of a cutter set 50A. Referring momentarily to Figure 2, elements 40a-40d are shown as comprising those cutter elements 40 that are positioned closest to bit axis 11. As shown in Figure 2, elements 40a, 40c are radially spaced from one another and are mounted in a first row 48 on blade 31, while cutter elements 40b, 40d are radially spaced from one another along a second row on blade 33. Cutter elements 40a-40d and their respective cutting faces 44 have different diameters and cutting profiles. Preferably,

cutter elements 40a, 40d have cutting faces 44 which are larger in diameter than cutter elements 40b, 40c. It is preferred that the cutting faces of elements 40a and 40d be approximately 19mm (0.75 inches) in diameter and that the smaller diameter cutters 40b, 40c have diameters of about 12 or 13mm (0.5 inches). Other sizes of cutting faces 44 may be employed. For example, cutter elements 40a, 40d may have cutting faces larger than 19mm (0.75 inches) diameter, and, for example, may be say 25mm (one inch) in diameter. In such instance, cutter elements 40b, 40c may have cutting faces 44 that are 19mm or 12mm or 13mm (0.75 or 0.5 inches) in diameter, as examples. As explained in more detail below, what is important to the present invention is that there be a difference in the radius of curvature between the cutting faces of cutter elements 40 within a set 50.

Cutter elements 40 in sets 50 are radially spaced such that each cutter 40 has a cutting profile that partially overlaps the cutting profile of adjacent cutter elements 40 in the same set 50. The degree or extent of overlap of cutting profiles of elements 40 in sets 50 may be varied within each set, and may also vary from set to set across the bit face 20. As shown in Figure 4, the common areas of intersection of the overlapping element cutting profiles form elongate-shaped regions 80 of double diamond density as the bit is rotated in the borehole. Region 80a is defined by the overlapping cutting profiles of cutter elements 40a and 40b, and region 80b is defined by the overlap in cutting profiles of cutter elements 40b and 40c. Likewise, region 80c is formed by the overlap in cutting profiles of elements 40c and 40d. On each side of a region 80 are regions 90 having single diamond density. As the cutter elements 40a-40d wear, the regions 90 of single diamond density wear relatively quickly compared to regions 80 of double diamond density. The variable wear patterns of set 50A and their benefits are described in more detail below with reference to Figure 6.

It is desirable to divide the large and small diameter cutter elements 40 in a set 50 among different blades 31-36. More specifically, and referring still to Figures 2 and 4, the large and small diameter cutters 40a-40d of set 50A are divided such that large diameter cutter element 40a and small diameter cutter element 40c are mounted on the same blade 31. Likewise, large diameter cutter element 40d and small diameter cutter element 40b are mounted on blade 33. Although the invention is depicted in Figures 1 and 2 on a six-bladed bit 10, the principles of the present invention can be employed in bits having any number of blades, and the invention is not limited to a bit having any particular number of blades or angular spacing of the blades.

Employing the cutter arrangement of the present invention, including the presently preferred embodiment, shown in Figure 4, provides enhanced bit stability, both before and after wear has occurred. Referring still to Figures 1, 2 and 4, as the bit 10 is rotated about its axis 11, the blades 31-36 sweep around the bottom of the borehole causing the cutter elements 40 to cut concentric troughs or kerfs within the formation material 54. More specifically, as blade 31 traverses the formation, elements 40a, 40c cut differing sized kerfs (60a, 60c respectively) in the formation leaving uncut formation material between the kerfs. As bit 10 continues to rotate, these uncut areas are removed by cutter elements 40 on other blades 31-36, including specifically by cutting elements 40b, 40d on blade 33 which themselves cut kerfs 60b, 60d. After one complete rotation of the bit, kerfs 60a-d will have been formed in the formation material. Between kerfs 60a-d are well defined ridges 70. Ridge 70a will remain between kerfs 60a and 60b after a rotation of bit 10. Likewise, ridge 70b will remain between kerfs 60b and 60c, and ridge 70c will separate kerfs 60c and 60d.

The cutter arrangement shown in Figure 4, which includes the positioning of a relatively small diameter cutter 40b (which has a relatively small radius of curvature) radially-adjacent to a larger cutter element 40a (one having a larger radius of curvature), creates ridges 70a and 70c that are higher than the ridges that would be created if identically-sized cutter elements were radially adjacent to one another. Providing higher ridges 70a, 70c between the kerfs in turn provides for increased stabilization for the bit, as the ridges 70a and 70c will tend to make the bit highly resistant to lateral movement due to the increased side loading imparted by the ridges to the cutter elements 40a-40d of set 50A. The bit 10 will thus tend to remain stable and resist bit vibration. This advantage is best understood by referring to Figure 5.

Shown in Figure 5 are cutter elements 40a-40c of set 50A as previously described with reference to Figure 4. Also shown in phantom by the dashed line is the cutting profile of a cutter element 40b' positioned in the same radial position R as element 40b. Element 40b', however, is shown to have a diameter equal to the diameter of element 40a. The height of ridge 70a formed by the overlap of cutter profiles of cutter elements 40a and 40b is shown to be equal to H. By contrast, if a large element 40b' were to be substituted for the smaller element 40b in set 50A, the resulting ridge height would be H' which, as shown in Figure 5, is less than H. Thus, using radially adjacent cutter elements 40a and 40b' having the same diameters would therefore provide less stabilization for the bit than that provided by set 50A of the present invention which includes radially-adjacent cutter elements 40a, 40b having differing radii of curvature. Although the element 40b' could be radially positioned such that the height H' could be made equal to H by moving the mounting position of element 40b' further from element 40a and away from the bit axis 11, such a bit would not include as many regions of

multiple diamond density, and would thus have the characteristics of a more light set bit, or at least of a bit that can not be made as "heavy set" as that provided by the present invention. More specifically, if the two smaller elements 40b and 40c of set 50A shown in Figures 4 and 5 were replaced in bit 10 by a single cutter element the same size as elements 40a and 40d, and if these three cutter elements were radially spaced such that their cutting profiles intersected at the same points that the cutting profile of element 40a intersects with 40b, and that 40c intersects with 40d as shown in Figure 4, then the height of ridges would all be equal to H (Figure 5); however, the region 80b of double diamond density would be absent from the rotated profile of the bit, and thus the durability of the cutting structure 14 and bit 10 would not be as great as that of the invention shown in Figure 4. As is apparent then, the cutter arrangement of set 50A as shown in Figure 4 in which cutter elements having large radii of curvature are disposed in radially-adjacent positions to cutter elements having small radii of curvature provides increased ridge height for enhanced stabilization and, at the same time, provides increased durability by providing an increased number of areas of multiple diamond density.

It can be appreciated that the stabilizing effects provided by cutter set 50A can be further increased by positioning similar sets 50A across the central portion 24 and shoulder portion 26 of the present drill bits. The stabilization provided by the present invention accrues primarily in central region 24 and shoulder portion 26. Thus, cutter sets 50A may or may not be disposed on gage portion 28.

Cutter set 50A also enhances bit stability even after substantial wear has occurred to cutting structure 14. Shown in Figure 6 is the set cutting profile of a worn cutter set 50A such as the cutting profile might appear

after drilling through a substantial amount of formation material, set 50A having a set cutting profile generally represented by the scalloped line designated by reference numeral 92. As shown, regions 80 of double diamond density tend to resist wear and thereby better retain their original cutting profiles, while the single diamond density regions 90 of cutter faces 44 are worn away to a greater degree. As wear becomes more pronounced, the regions of double diamond density 80 will present a relatively sharp and highly exposed cutting profile to the formation material as compared to the worn away single diamond density regions 90. The relatively sharp scribe shaped regions 80 will then create grooves and stabilizing ridges as the bit drills through formation material, these grooves being formed at substantially the same radial position that ridges 70a-70c shown in Figure 4 were created.

Bit stabilization after wear has occurred to the bit cutting structure is further enhanced by the present invention due to its use of radially adjacent large and small cutter elements 40 in sets such as set 50A. Referring again to Figure 6, by positioning smaller cutter elements 40b, 40c radially-adjacent to one another and between large cutter elements 40a and 40d (in rotated profile), the tip 81b of double diamond density region 80b (that point most exposed to the formation material) will project further into the formation than will the tips 81a and 81c of regions 80a and 80c. This arrangement thus creates stabilizing ridges of formation material between double diamond density regions 80a and 80b, and between regions 80b and 80c, the height of the ridges being at least as great as the difference between the exposure height of tip 81b relative to tips 81a or 81c, such difference represented by dimension arrow 102 in Figure 6. Thus, positioning adjacent cutter elements so as to provide elongate regions 80 of multiple diamond density across the span of a set cutting profile, and across the bit face 20,

helps the bit maintain an aggressive cutting structure and a high ROP, and prolongs the useful life of the bit. Simultaneously, the regions of multiple diamond density provide a stabilizing effect on the bit and lessens the likelihood of damaging bit vibration occurring as the bit wears.

The use of relatively large and small cutter elements 40a-40d in set 50A has an additional advantage over the cutter arrangements in the prior art that employed all large or all small cutter elements in the same region of the bit face 20. Due to their relatively close positioning to one another, the large and small cutter elements 40a and 40b, for example, will apply substantially the same force to the formation; however, due to the difference in the elements' radii of curvature, the forces applied through the smaller cutter 40b will be more concentrated or directed. This is because the resultant vector of forces applied to the formation are concentrated in a smaller arcuate area of the cutter element 40b compared to the larger element 40a. In certain types of formations, this allows the smaller cutter elements 40b, 40c to prefracture the formation material, allowing the larger cutter elements 40a, 40d to remove the prefractured material more easily and with less wear than would otherwise be the case if no prefracturing occurred. This, in turn, decreases the drilling torque required to drill the borehole.

In contrast to the present invention, if, instead of using smaller elements 40b, 40c, another or additional large diameter elements were used, the forces applied through the larger cutters may not be concentrated enough to provide for the desirable prefracturing. Alternatively, if only small cutter elements were employed in a particular region of the bit, so as to apply the more concentrated forces to the formation, the bit would lack the substantial benefits provided by large diameter cutters, those benefits including the increased or enhanced shearing capabilities

which are desirable in certain formations. Thus, the invention combines the high shearing efficiency provided by large cutters with the high penetration forces provide by smaller cutters. Further, providing smaller cutter elements on the bit face lowers the cost to manufacture the bit as compared to a similar bit that employs all large cutters because it is less expensive to manufacture smaller cutter elements than larger ones. Thus, the cutter arrangement shown in Figure 4 provides certain of the advantages that small and large cutter elements provide individually, as well as the added benefits that have been described above that result from the combination of large and small elements in radially adjacent positions.

Referring again to Figure 4, it is preferred that cutter set 50A include other cutter elements 40 that have the same cutting profiles as some or all of the elements 40a-40d. Such cutter elements are mounted on the bit face 20 at substantially the same radial position as elements 40a-40d, but are positioned in blades other than 31 and 33. So positioned, these elements therefore follow in the same swath or kerf cut by a preceding cutter element 40 of set 50A. As used herein, such elements may be referred to as "redundant" cutters. Redundant cutters increase the durability and life of the bit 10 by increasing the diamond density, and thus ensure that well defined stabilizing grooves are formed in the formation material. In the rotated profile of Figures 3-6, the distinction between such redundant cutter elements cannot be seen; however, the arrangement may be understood with reference to Figure 2 where cutter elements 40e and 40f are positioned on bit face 20 so as to be redundant to cutters 40a and 40c, respectively. In this arrangement, and referring to Figure 4, regions of multiple diamond density 80 would have triple diamond density. Redundant cutters may be employed for any cutter element 40 in any set 50, and are of greatest benefit when located at radial positions on the

bit face that are subjected to particularly severe loading, such as at locations in the central portion 24 or shoulder portions 26 of bit face 20.

Certain variations or alternative embodiments to the drill bit and cutter arrangement previously described are shown in Figures 7-10. In describing these embodiments, similar reference numerals and characters will be used to identify like or common elements.

Although set 50A has thus far been depicted and described as including radially spaced cutter elements 40a-40d (and redundant cutter element 40e, 40f), the invention is not limited to having a particular number of cutter elements 40 in a set 50. That is, a set 50 may include three, four or any larger number of radially-spaced elements 40, and may also include any desirable number of redundant elements. Further, the invention is not limited to any particular ratio of large cutter elements to small elements within a set 50. For example, and referring now to Figure 7, there is shown radially-adjacent cutter element sets 50B and 50C. Cutter element set 50B includes five cutter elements 40g-40k, while 50C includes four cutter elements 40k-40n. In this embodiment, cutter element 40k is a member of both sets 50B and 50C. Cutter elements 40h-40j and 40l-40m have cutting faces with relatively small diameters in comparison to cutter elements 40g, 40k, 40n, such that the ridges that are formed in the formation material by sets 50B and 50C will be higher (and thus will provide greater stabilization to the bit) than would be the case if cutter elements having the same size as elements 40g, 40k, 40n were disposed between elements 40g and 40k and between 40k and 40n.

Another alternative embodiment of the invention is shown in Figure 8 which shows a cutting structure 14 having two cutter element sets 50D and 50E, each of which includes three radially-spaced cutter elements. As shown, cutter element sets 50D and 50E each include three cutter elements

having generally circular cutting faces of differing diameters. More specifically, cutter element set 50D includes elements 40o-40q and set 50E includes elements 40r-40t. Each set 50D and 50E preferably includes redundant cutter elements (not shown). Cutter elements 40o, 40r have relatively large diameters, as is advantageous for efficient shearing when drilling, and may be 0.75 inch (approx. 19mm) in diameter, for example. Elements 40p, 40s are chosen to have smaller cutting faces and, for example, may be 12mm or 13mm (0.5 inch) in diameter. Elements 40p and 40q are mounted such that, in rotated profile, their cutting profiles overlap with the cutting profiles of elements 40o and 40r, respectively. Cutter elements 40q and 40t have cutting faces that are larger than those of cutters 40p and 40s, but are smaller than those of elements 40o and 40r and, for example, may have diameters equal to 0.625 inch (approx. 16mm). Elements 40q and 40t are radially spaced such that in rotated profile, their cutting profiles will overlap with the cutting profiles of cutter elements 40p and 40s, respectively. With this arrangement, the highest stabilizing ridges will be formed between elements 40o and 40p and between elements 40r and 40s due to the more extreme difference in curvature of these pairs of elements than between elements 40p and 40q and between 40s and 40t. A cutting structure 14 such as that shown in Figure 8 may be preferred over that shown in Figure 4 for drilling in softer formations where more shearing is desired and where prefracturing is not especially advantageous.

To further enhance stabilization of the bit 10, the exposure height of the elements 40 within a set can be varied. For example, referring to Figure 9, a cutter set 50F is shown comprising cutter elements 40u-40x. Cutter elements 40v and 40w are smaller than cutter elements 40u and 40x and thus have cutting faces with smaller radii of

curvature than the larger elements 40u and 40x. As previously explained with reference to Figures 4 and 5, this arrangement alone provides an enhancement in stabilization. In set 50F, however, elements 40u and 40x are mounted on the bit face so as to be more exposed to the formation material than smaller elements 40v and 40w. As compared to cutter set 50A shown in Figure 4, where all the cutter elements were mounted at substantially the same exposure height, the cutter arrangement of set 50F increases the size of the stabilizing ridges 70a and 70c that are formed as the bit is rotated, and thus provides for enhanced stabilization for the unworn bit.

An increased measure of stabilization for a partially worn bit can also be achieved using the principles of the present invention. Referring to Figure 10, cutter element set 50G is shown having relatively small diameter cutter elements 40bb and 40cc mounted so as to be more exposed to the formation material than the larger cutter elements 40aa and 40dd which flank elements 40bb, 40cc in rotated profile. Employing this arrangement, the stabilizing ridges 70a and 70c that are initially formed when the unworn bit is rotated will be smaller than those formed by set 50A of Figure 4; however, after the bit has become partially worn, the difference in exposure height as between tips 81b and 81a (and between 81b and 81c) of multiple diamond density regions 80 as designated by reference numeral 102 will be even greater than that shown in Figure 6 for set 50A. The arrangement of set 50G will thus create deeper grooves and higher stabilizing ridges after wear has occurred to the cutting structure of the bit, as compared to that of set 50A of Figure 4.

While the preferred embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the scope of the present invention. The embodiments described herein are exemplary only, and are not limiting. Many variations

and modifications of the invention and the principles disclosed herein are possible and are within the scope of the invention. For example, cutter elements may be positioned on the bit with back rake or forward rake. Accordingly, the scope of protection is not limited by the description set out above, but is only limited by the claims which follow.

## CLAIMS

1. A drill bit for drilling through formation material when the bit is rotated about its axis, the drill bit comprising:

a bit body including a bit face having a plurality of radially disposed blades angularly spaced from one another; and,

cutter elements disposed in rows on the blades and having cutting faces oriented so as to cut kerfs in the formation material when the bit is rotated about its axis, the cutter elements including a first plurality with cutting faces having a radius of curvature, a second plurality with cutting faces having a radius of curvature that is less than the radius of curvature of the cutting faces of the first plurality, and a third plurality with cutting faces having a radius of curvature that is greater than the radius of curvature of the cutting faces of the second plurality, at least one of the blades having a row of cutter elements that includes cutter elements from at least two of the first, second and third pluralities;

wherein the cutter elements are arranged in sets of cutter elements on the bit face, each of the cutter elements of the sets having a cutting profile that, in rotated profile, partially overlaps with the cutting profile of at least one other cutter element of the same set;

wherein a first set includes a first cutter element of the first plurality mounted on a first blade at a first radial position relative to the bit axis, a second cutter element of the second plurality mounted on a second blade at a second radial position relative to the bit axis such that the cutting profile of the second cutter element partially overlaps in rotated profile with the cutting profile of the first cutter element, and a third cutter

element of the third plurality mounted at a third radial position relative to the bit axis; and,

wherein the second radial position is between the first and the third radial positions.

2. A drill bit according to claim 1, wherein the third cutter element of the first set is mounted such that, in rotated profile, the cutting profile of the third cutter element partially overlaps with the cutting profile of the second cutter element.

3. A drill bit according to claim 1 or claim 2, wherein the radius of curvature of the cutter faces of the third plurality is substantially equal to the radius of curvature of the cutter faces of the first plurality.

4. A drill bit according to claim 1 or claim 2, wherein the radius of curvature of the cutter faces of the third plurality is greater than the radius of curvature of the cutter faces of the first plurality.

5. A drill bit according to claim 1 or claim 2, wherein the radius of curvature of the cutter faces of the third plurality is less than the radius of curvature of the cutter faces of the first plurality.

6. A drill bit according to any of claims 1 to 5, wherein the first set further comprises a fourth cutter element having a cutting face with a radius of curvature that is substantially equal to the radius of curvature of the second cutter element, and wherein the fourth cutter element is mounted such that, in rotated profile, the cutting profile of the fourth cutter element partially overlaps with the cutting profile of the second cutter element.

7. A drill bit according to any of claims 1 to 6, wherein each of the blades of the bit face includes a row of cutter elements that includes cutter elements from at least two of the first, second and third pluralities.

8. A drill bit according to any of claims 1 to 6, wherein said first blade includes a row of cutter elements that includes cutter elements from all of the first, second and third pluralities.

9. A drill bit according to claim 8, wherein each of the blades of the bit face includes a row of cutter elements that includes cutter elements from all of the first, second and third pluralities.

10. A drill bit according to claim 1, wherein the first set further comprises a fourth cutter element having a cutting face with a radius of curvature that is substantially equal to the radius of curvature of the second cutter element, and wherein the fourth cutter element is mounted at a radial position that is between the second and third cutter elements when viewed in rotated profile, and wherein the radius of curvature of the cutter faces of the third plurality is greater than the radius of curvature of the cutter faces of the first plurality.

11. A cutting structure for a drill bit, the cutting structure comprising:

a bit face having a central axis;

cutter elements having cutting profiles and generally circular cutting faces mounted on the bit face in radially-disposed rows on blades, the cutter elements including a first plurality having cutting faces of a first diameter, a second plurality having cutting faces of a second diameter that is smaller than the first diameter, and a third

plurality having cutting faces of a third diameter that is larger than the second diameter;

wherein a first and a second of the rows of cutter elements each includes cutter elements from the first and the second pluralities, the cutter elements in each of the first and second rows being radially spaced from one another;

wherein the cutter elements are mounted on the bit face in sets of cutter elements, a first set including a first cutter element of the first plurality and a second cutter element of the second plurality mounted in separate ones of the rows of cutter elements and at different radial positions relative to the axis such that, in rotated profile, the cutting profiles of the first and the second cutter elements partially overlap and such that the first cutter element is mounted closer to the axis than the second cutter element, the first set further including a third cutter element of the third plurality mounted on the bit face at a third radial position that is further from the axis than the first and the second radial positions; and,

wherein at least two of the first, second and third cutter elements reside on one of said blades.

12. A cutting structure according to claim 11, wherein the first set further includes a plurality of the cutter elements having cutting faces of the second diameter that are mounted on the bit face at radial positions between the second and the third radial positions.

13. A cutting structure according to claim 11 or claim 12, wherein the third diameter is larger than the first diameter.

14. A cutting structure according to claim 11 or claim 12, wherein the third diameter is smaller than the first diameter.

15. A cutting structure according to claim 11 or claim 12, wherein the third diameter is substantially the same size as the first diameter.

16. A cutting structure according to any of claims 11 to 15, wherein the rows include cutter elements of the first, second and third plurality of cutter elements.

17. A drill bit according to claim 1, wherein the cutter elements have generally circular cutting faces, and wherein the first set further comprises a plurality of redundant cutter elements mounted on the bit face at the first radial position, the redundant cutter elements at the first radial position having cutting faces that are substantially the same in diameter as the first cutter element.

18. A drill bit according to claim 17, wherein the first set further comprises a plurality of redundant cutter elements mounted on the bit face at the second radial position, the redundant cutter elements at the second radial position having cutting faces that are substantially the same in diameter as the second cutter element.

19. A drill bit according to any of claims 1, 17 or 18, wherein the cutter elements in the first set have substantially the same exposure height.

20. A drill bit according to any of claims 1, 17 or 18, wherein the second cutter element of the first set is mounted on the bit face so as to be less exposed to the formation material than the first cutter element of the first set.

21. A drill bit according to any of claims 1, 17 or 18, wherein the second cutter element of the first set is mounted on the bit face so as to be more exposed to the formation material than the first cutter element of the first set.

22. A drill bit according to any of claims 1 or 17 to 21, wherein the bit face includes a central portion, a gage portion, and a shoulder portion between the gage portion and the central portion, and wherein the cutter elements of the first set are mounted on the bit in the shoulder portion.

23. A drill bit according to any of claims 1 or 17 to 22, wherein the third cutter element has a radius of curvature that is greater than the first radius of curvature.

24. A drill bit according to any of claims 1 to 10 or 17 to 23, wherein the cutter elements are polycrystalline diamond cutting elements.

25. A drill bit, substantially as described with reference to Figures 1 to 3 in conjunction with any of Figures 4 to 6, 7, 8, 9, and 10 of the accompanying drawings.

26. A cutting structure for a drill bit, substantially as described with reference to Figures 1 to 3 in conjunction with any of Figures 4 to 6, 7, 8, 9, and 10 of the accompanying drawings.